

**Final Report**

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**SRM Internal Flow Tests  
and  
Computational Fluid Dynamic Analyses**

**Volume I  
Major Task Summaries**

November, 1995

**Prepared for:  
George C. Marshall Space Flight Center  
National Aeronautics and Space Administration  
Marshall Space Flight Center, AL 35812**

**Contract NAS8-39095**

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## **PREFACE**

This report was prepared by the Huntsville Operation of ERC, Incorporated for the Fluid Dynamics Division of the Science and Engineering Directorate, George C. Marshall Space Flight Center, National Aeronautics and Space Administration. This effort was performed under Contract NAS8-39095 with Jack E. Hengel, ED34, serving as the Contracting Officer's Technical Representative. The period of performance covered by this report is August, 1991 through October, 1995.

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## **Introduction**

During the four year period of performance for NASA contract, NAS8-39095, ERC has performed a wide variety of tasks to support the design and continued development of new and existing solid rocket motors and the resolution of operational problems associated with existing solid rocket motors at NASA/MSFC. This report summarizes the support provided to NASA/MSFC during the contractual period of performance. The report is divided into three main sections. The first section presents summaries for the major tasks performed. These tasks are grouped into three major categories: full scale motor analysis, subscale motor analysis and cold flow analysis. The second section includes summaries describing the computational fluid dynamics (CFD) tasks performed. The third section, the appendices, of the report presents detailed descriptions of the analysis efforts as well as published papers, memorandums and final reports associated with specific tasks. These appendices are referenced in the summaries. The subsection numbers for the three sections correspond to the same topics for direct cross referencing.

## **1.0 MAJOR TASKS SUMMARIES**

### **1.1 Full Scale Motor Analyses**

ERC provided support and performed investigative analyses on several full scale solid rocket motors for NASA/MSFC during the performance period of this contract. The nature of this support included design verification analyses to evaluate motor designs and uncover potential operational problems, analyses to support problem resolution for existing operational motors, generation of analysis level engineering drawings and support in generating thermal, mechanical and chemical motor boundary conditions for analyses. The full scale motors investigated include the SRMU for Titan IV, ASRM and RSRM. Summaries of the major analyses performed by ERC for each of these motors are contained in this section.

#### **1.1.1 RSRM Motor Analyses**

ERC has supported continued RSRM development as well as RSRM operational problem resolution through the RSRM Chief Engineer's Office of NASA/MSFC. This effort included generation of analysis drawings and boundary conditions, evaluation of proposed motor changes, participation in problem resolution investigation teams and related analysis support to resolve issues of concern associated with the motor. The major analysis activities are highlighted in this section.

##### **1.1.1.1 Pressure Perturbation Investigation**

A pressure perturbation investigation directed by NASA was initiated to determine the source of the motor problem which triggered the out of family pressure blip observed

during the flight of STS-54, RSRM-29B. ERC began participation in this investigation in January of 1993. The investigation was multi-faceted and involved review and analysis of flight and ground test measurements, formulation and evaluation of possible causes of the pressure blip, design of cold flow and subscale motor tests to support hypothesized causes and CFD analysis of the flow field environments in support of the resolution of this problem.

ERC was involved in investigating several proposed hypotheses and was able to gather considerable evidence that slag ejection was the most probable cause. A slag ballistics model was developed and validated by a cold flow slag ejection model. This analytical model relates the magnitude and duration of the pressure spike to the total slag weight ejected. A number of cold flow models were developed in response to the need for supporting data to resolve the cause of the problem. ERC proposed nozzle modifications to an existing Thiokol spin motor in an effort to gain knowledge on why some solid rocket motors are more prone to slag generation and expulsion than others. Section 3.1.1.1 provides a more complete description on this topic. The appendix also contains an AIAA paper entitled "The Effects of Slag Ejection on Solid Rocket Motor Performance." This paper was presented at the 1995 AIAA Joint Propulsion Conference in San Diego and has subsequently been awarded the 1995 Solid Rockets Best Paper Award.

#### **1.1.1.2 NBR Stiffness Investigation**

Concern over the stiffening of the NBR material used in the nozzle flex boot, the nozzle bearing and the field joint inhibitors fueled the creation of an NBR Stiffness Investigation Team. The concern centered around the torque loads which would be required to gimbal the nozzle with the stiffer material as well as how the increased stiffness would affect field joint performance and slag accumulation in the motor. ERC participated in the investigation team data review meetings and provided a plan which included CFD analysis and cold flow model testing to provide further data to resolve NASA concerns. The cold flow work centered around the design of an inhibitor dynamics model to allow testing of simulated aft and center joint inhibitors and their effect on the oscillating chamber pressure as related to the stiffer NBR material. The cold flow analyses determined that the overall coupled effects associated with the stiffer NBR material would have the effect of reducing oscillating motor pressure amplitudes. The final review package, "Inhibitor Stiffening Evaluation (NBR)", dated 22 December 1994, provides more details of this effort.

A coupled fluid dynamics/structural stress analysis along with a two-phase flow analysis was performed on the motor inhibitors. It was concluded from the analysis that the stiffer NBR material would have a negligible effect on slag accumulation in the submerged nozzle region. Section 3.1.1.2 provides details of this analysis.

### **1.1.1.3 Nozzle O-Ring Investigation**

Observance of smoke stain paths in the radial and axial bondlines of the flight motor nozzle nose inlet assembly prompted an investigation into the cause of this event. ERC reviewed technical data and analysis results generated by Thiokol to support their conclusions regarding the origins and timing of these events. As a result, ERC designed a subscale nozzle joint test which used full scale joint dimensions for gap widths, lengths, and materials. An appropriate test motor was also selected. ERC also provided information on nozzle joint pressures and recovery temperatures which were used by NASA/MSFC personnel in thermal and flow analyses of the joints to determine possible communicating voids in the o-ring grooves in the nozzle joints. Details of this investigation can be found in Section 3.1.1.3.

### **1.1.1.4 Analysis Drawings**

Ordinarily, assembly level drawings do not have the detailed dimensions necessary for various engineering analysis needs. ERC generated engineering analysis drawings of all major subassemblies for the RSRM by using drawings for the detailed individual parts. The detailed drawings were "assembled" into major component drawings so that the major subassemblies with detailed dimensions were available as needed for flow, thermal, or structural analysis purposes. Section 3.1.1.4 contains a complete list of the drawings generated.

### **1.1.1.5 Internal Aerodynamic Torque**

NASA/MSFC revisited the load requirements on the RSRM TVC system actuators. ERC provided support to the fluid dynamics division of NASA/MSFC by calculating the forces and moments on the interior surface of the RSRM nozzle from CFD data that was obtained from NASA/ED32. The results of the integration were used by ED32 for CFD code validation. A number of test cases were used to confirm the computations including analytical solutions and data from the ASRM nozzle model. Section 3.1.1.5 contains more information on this task.

### **1.1.1.6 External Aerodynamic Torque**

Due to an interest in extending the nozzle aft exit cone in order to increase RSRM performance and thus allow for increased payload carrying ability, ERC calculated external forces and moments on the proposed RSRM aft exit cone nozzle extension. ERC also examined data previously generated for the SRM which provided static pressures on the external surface of the nozzle. The forces and moments at conditions of interest were calculated for the nominal nozzle as well. These values were subsequently used to update the values in the Design Loads Data Handbook. A memorandum covering this effort is located in Section 3.1.1.6.

#### **1.1.1.7 Extended Aft Exit Cone**

In an effort to increase Shuttle payload capability by increasing the specific impulse of the solid boosters, a modification to the RSRM nozzle aft exit cone was proposed. ERC assembled relevant documents and drawings to investigate two potential gas dynamic related problems associated with the modification. These included the methodology used to generate the curvature of the exit cone extension and its impact on the existing two-phase phenomena of particle impingement near the end of the current nozzle which could be exacerbated by the nozzle extension. The analysis showed that the thermal and erosion safety margins at the nozzle exit were less than those determined by Thiokol in the PDR Thermal Erosion Report, TWR-66484. The projected safety margin showed the extreme marginality of the design and pointed to some risk of not meeting requirements for the two qualifying ground static tests planned before the first flight.

#### **1.1.1.8 150 Inch Case Design Review**

ERC reviewed a 150 inch RSRM case design proposed to increase shuttle cargo and orbit capabilities. ERC advised that design changes may provide increased impulse with programmatic advantages, but the internal motor environment will be altered including effects on slag accumulation. It was advised that detailed flow analyses and testing be performed in conjunction with thermal/erosion analyses to reverify insulation margins and to evaluate effects of slag ejection on motor performance.

#### **1.1.2 Titan Motor Failure Analysis**

After the failure of the Titan IV Solid Rocket Motor Upgrade (SRMU) NASA/MSFC was requested to investigate possible causes of the motor failure. ERC supported the NASA/MSFC failure investigation and assisted in narrowing the investigation to possible problems in the region of the aft field joint. A coupled fluid dynamics/mechanical stress analysis was performed on the aft field joint and the motor propellant in this region in conjunction with NASA/MSFC. The analysis was able to show that there was a continual increase of flow field resistance at the aft slot due to the aft segment propellant grain being progressively moved radially toward the centerline of the motor port. It was concluded that this "bootstrapping" effect between the grain radial movement and the internal flow resistance was conducive to causing a rapid motor failure. The final report of this analysis is contained in Section 3.1.2.

#### **1.1.3 ASRM Motor Design Verification Analyses**

ERC participated in the process of ASRM motor design evaluation and verification in support of the fluid dynamics division of NASA/MSFC. This effort included the review of proposed motor component designs, generation and evaluation of motor component environments and performance of motor components including the igniter, motor field

joints, forward, center and aft propellant grains, and submerged nozzle and nozzle joints. Major analysis activities performed for the ASRM project are highlighted in this section.

### **1.1.3.1 Motor Port Environment Analysis**

As part of the overall ASRM design evaluation effort, ERC provided support by reviewing internal component designs and performing appropriate CFD analyses to determine the flow induced thermal and mechanical environments in the region of the major internal motor components. This investigation included analysis of all the field joints and the motor nozzle. The investigation also provided information to support other NASA/MSFC thermal and mechanical analyses concerned with evaluating motor performance. The internal motor environment analyses revealed no design problems associated with any of the components investigated. Further details and conclusion from these analyses are contained in section 3.1.3.1.

### **1.1.3.2 Structural/Fluid Dynamic Stress Analysis**

After the Titan SRMU failure due to a poorly designed field joint, NASA/MSFC became interested in verifying the ASRM field joint design by performing a detailed deformation analysis of the field joint. An ERC/Sverdrup team was formed to perform this coupled fluid dynamic/structural propellant analysis to determine the deformed grain geometry in the vicinity of the ASRM forward and aft field joints. The analysis concluded that the deformations on the propellant field joints were not excessive and the possibility of motor failure as a result of fluid dynamic loading was not a problem. Section 3.1.3.2 contains a detailed presentation of the method used to perform this analysis along with a detailed discussion of the analysis.

### **1.1.3.3 Igniter Analysis**

An investigation into the ASRM igniter design was initiated after ERC's PDR design review of the igniter generated a formal concern with the design of the igniter ports. The sharp edged circular and oblong ports cut into the aft dome of the filament wound case was the issue of concern. It was felt that this design would result in low discharge coefficients and therefore higher chamber pressures than would be predicted using equivalent nozzle area ballistics predictions as performed by Aerojet. The higher chamber pressures would affect the igniter design. ERC performed analytic calculations examining the problem and designed a cold flow test apparatus to examine this phenomena and analyzed the test results. The first open air firing of the multi-port igniter indeed confirmed a higher than predicted chamber pressure. Although the higher chamber pressure was initially attributed to an elevated burn rate, the cold flow test performed by the Fluid Dynamics Division confirmed a reduced nozzle discharge coefficient was the principal problem. The igniter design was updated to account for this phenomena.

#### **1.1.3.4 Internal and External Nozzle Torque Analysis**

This project dealt with calculating the forces and moments on the interior surfaces of the ASRM nozzle in order to evaluate the load requirements on the ASRM TVC system actuators. Surface pressure data was obtained from NASA/ED32 and integrated to obtain moments. The results from the analysis were used by ED32 for CFD code validation. Further details of this investigation can be found in section 3.1.3.4.

#### **1.1.3.5 Analysis Drawings**

Since a large amount of engineering analysis was required to evaluate the design of the ASRM motor components and since assembly level drawings do not ordinarily have the detailed dimensions necessary for these engineering analyses, ERC generated engineering analysis drawings of all major subassemblies for the ASRM by using drawings for the detailed individual parts. The detailed drawings were "assembled" into major component drawings so that the major subassemblies with detailed dimensions were available as needed for flow, thermal, or structural analysis purposes. Section 3.1.3.5 contains a complete list of the drawings generated.

### **1.2 Subscale Motor Analyses**

ERC provided subscale motor test support to NASA/MSFC by formulating subscale tests to simulate full scale motor phenomena, performing test design, providing test planning and performing test data analysis. Tests supported include the NITM two-inch motor test, the five-inch spin motor test, the ASRM subscale plume test and the RSRM nozzle joint test.

#### **1.2.1 NITM Two-Inch Motor Analysis**

ERC was asked to review the NITM Test 3 pressure measurement data because of apparent mismatches between the data from the first three and the last two material test rings. The measurement data was reviewed and CFD analysis of the motor was performed to determine that the pressure gauges in rings 1, 2, and 3 were miscalibrated. ERC was able to salvage the utility of the Test 3 erosion measurements by devising a method for recalibrating the Test 3 pressure data a posteriori. A complete summary of this analysis is presented in Section 3.2.1.

#### **1.2.2 Five-Inch Spin Motor Design and Test Analysis**

It was determined that pressure perturbations in the RSRM are caused by the periodic expulsion of molten aluminum oxide slag from a pool that collects in the aft end of the motor around the submerged nozzle nose during the last half of motor operation. It



was suspected that some motors produce more slag than others due to differences in aluminum oxide agglomerate particle sizes that may relate to subtle differences in propellant ingredient characteristics such as particle size distributions or processing variations. ERC used its' expertise in this area and CFD analysis to design a subscale motor experiment to determine the effect of propellant ingredient characteristics on the propensity for slag production. An existing five inch ballistic test motor was selected as the basic test vehicle. The standard converging/diverging nozzle was redesigned with a submerged nose nozzle to provide a positive trap for the slag that would increase the measured slag weights. ERC also participated in the analysis of the post test data and performed CFD analyses which were compared to the spin motor test data. The CFD analyses resulted in the publishing of AIAA paper 96-2780 which was presented at the 32nd AIAA Joint Propulsion Conference. The AIAA paper detailing this analysis is in Section 3.2.2.

### **1.2.3 ASRM Subscale Plume Test**

Due to the greater aluminum content of the ASRM propellant as compared to the RSRM propellant, NASA/MSFC became interested in measuring plume radiation from the ASRM propellant. ERC supported this test by providing a new nozzle design. Drawings were provided for the subscale graphite nozzle which incorporated a steel nozzle body shell to contain the graphite insert and prevent the graphite from experiencing tensile stresses which may have caused longitudinal cracking observed on earlier tests. The nozzle expansion section was a scaled ASRM contour and the contraction section was a hyperbolic spiral extending forward to a point at which it became tangent to the entrance ramp angle. A thermal analysis of the ASRM subscale nozzle exit cone was performed which assured that there would be no melting of the steel section of the nozzle. It was also found that there would be no degradation of the nozzle bearing surfaces or the o-ring grooves. A detailed discussion of the analysis can be found in Section 3.2.3.

### **1.2.4 RSRM Subscale Nozzle Joint Tests**

Observance of smoke stain paths in the radial and axial bondlines of the flight motor nozzle nose inlet assembly prompted an investigation into the cause of this event. ERC reviewed preliminary data packages for initial tests of Joints #3 and #4 subscale models and made recommendations on data scaling and on plans for future model and propellant changes. Plugging of the joint flow paths is a primary issue as it has a drastic influence on the joint response to the environment and therefore on the data used to calibrate the thermal models used by ED66.

## **1.3 Cold Flow Analyses**

The Solid Rocket Motor Air Flow Facility (SAF) was constructed for the purpose of evaluating the internal propellant, insulation, and nozzle configurations of solid rocket motor designs. ERC supports NASA/MSFC in utilization of the facility by performing a

variety of task including model formulation and design, instrumentation requirements generation, test planning, data reduction, data analysis and CFD model verification analysis. ERC supported NASA/MSFC in this area by performing the following tasks.

### **1.3.1 Checkout Model Analysis**

The SAF Checkout Model was a simple cylindrical port model with a converging/diverging nozzle which was designed and tested to provide information necessary to properly qualify the capabilities of the cold flow facility. ERC supported ED34 in the areas of setting model design requirements, test planning, instrumentation planning, data analysis and problem resolution. ERC also performed 3-D CFD analyses of the model from the header pipes through the diffuser which were able to predict the proper operation of the facility prior to testing. Several flow instrumentation problems were discovered during analysis efforts and corrected. ERC also investigated the need for including air heaters in the SAF and determined that the change in absolute temperature during a test run could be adequately accounted for by the data analysis program. Thermal analysis also concluded that temperature drops of the air at different locations in the facility did not violate safety margins. The details of this analysis can be found in Section 3.3.1.

### **1.3.2 ASRM/Technology Model**

As part of NASA/MSFC's role of verifying the design of the ASRM motor, the ASRM project office became interested in testing a scaled cold flow model of the ASRM motor which would as closely as possible replicate the flow field features of the ASRM motor. The model was to be a very high fidelity model of the ASRM including the submerged nozzle, all field joints as well as the forward star grain section and including wall mass injection to simulate the burning propellant. ERC generated design requirements for a 10% scale porous wall ASRM model to respond to this request. The scope of this support included the creation of conceptual drawings for the model, generating detailed requirements for model operating conditions and developing model instrumentation requirements. A stepped process instrumentation installation plan was developed to assure that the integrity of the model would not be compromised before some information could be garnered as to the effect that installed instrumentation would have on the model flow field. Flow field analyses were performed to assure that the flow throughout the model was properly scaled to the full scale ASRM. ERC performed experimental tests and CFD analyses to determine the model liner material and porosity which best represented the full scale ASRM propellant surface mass addition environment. A thorough study was also done to determine the total pressure drop through all the model plumbing and to the model nozzle exit. Finally, a build plan was developed for the model so that not only was the model to provide full scale Reynold's Number data on the ASRM, but would be used as a technology test bed to evaluate the latest cold flow testing methods and instrumentation. Further details of this analysis are contained in Section 3.3.2.

### **1.3.3 ASRM Aft Section/Nozzle Model**

NASA/MSFC directed ERC to design an ASRM aft section/nozzle model to investigate in more detail the submerged nozzle region of the motor at various nozzle cant angles. ERC was involved in all phases of the model development and testing including the generation of detailed model requirements and conceptual drawings, the planning of types and locations of the instrumentation, the design of a velocity profile plate to provide a Culick velocity profile upstream of the nozzle nose, design drawings review, test planning and data reduction and analysis for the model. During the data reduction and analysis portion of the task, a performance program was constructed to analyze the data from the model test and provide graphical and tabular reduction of the test data to calculate the forces and moments on the model nozzle from the experimental model wall pressures. A complete discussion of this effort and the results can be found in the AIAA paper 94-3292 written on this model and contained in Section 3.3.3.

### **1.3.4 ASRM Aft Section/Nozzle Water Flow Model**

NASA/MSFC tested a water flow model to provide a better understanding of the ASRM submerged nozzle region using flow visualization. In order to more accurately represent the full-scale ASRM motor port upstream of the nozzle entrance, a drilled-hold plate was used in an attempt to achieve a Culick velocity profile. During testing of the ASRM aft segment/nozzle water flow model, NASA/MSFC discovered irregularities in the desired Culick velocity profile upstream of the model nozzle. ERC investigated these irregularities and utilized CFD to determine that the irregularities were indeed due to the plate design. Section 3.3.4 contains further details of the analysis.

### **1.3.5 SAF Loss of Storage Tank Investigation**

NASA/MSFC ED34 requested ERC to investigate the implications of the loss of a single 1250 cubic feet air storage tank on the performance capabilities of the SAF. The investigation concluded that the loss of a single tank would not adversely affect any of the tests planned at this facility, or any repeat of the tests that have already been performed. Suggestions were presented to assist in optimization of the facility operation under the condition of reduced air storage capacity. Further details of this work are contained in Section 3.3.5.

### **1.3.6 SAF Model Test Plan**

As part of ERC's test plan support to NASA/MSFC/ED34, an overview plan was developed to outline SAF (Solid Rocket Motor Air Flow) testing with the 1) RSRM Scaled Nozzle Slag Ejection Model, 2) the RSRM NBR Inhibitor Dynamics Model and 3) the RSRM 10% Scale Full Length Porous Wall Model. These plans included consideration of immediate needs and anticipated future needs and opportunities at the time of writing. The complete plan is contained in Section 3.3.6.

### **1.3.7 ASRM Igniter Exhaust Port Model**

In order to resolve concerns over the operation of the ASRM Igniter, ERC designed a cold flow model and formulated test plans for a series of tests to provide data on the discharge coefficients of the ASRM igniter ports. A pretest report, contained in Section 3.3.7, for the experiment provided predictions on the pressure drops and performance of the igniter hole plates. The experimental data was analyzed and discharge coefficients were determined for the circular holes, the elliptical holes, and the chamfered holes of each geometric configuration. Finally, a total discharge coefficient was determined for the multi-port ASRM igniter which is composed of one circular hole and eleven elliptical holes.

### **1.3.8 RSRM Nozzle Slag Ejection Precursor Tests**

ERC developed this coldflow model in response to the desires of the RSRM Chief Engineers Office to quickly plan, build, test, and analyze a model which would provide data on the slag ejection phenomenon which was thought to be responsible for the pressure blip observed in RSRM motors. ERC developed a plan to use the Checkout Model with modifications to allow the injection of water into the model to simulate the molten aluminum slag accumulating in the motor. A pretest plan was written which outlined the reasons for the test, the instrumentation requirements for the tests, and the test conditions. The test data supported the fact that water expulsion from the model does correlate well with the occurrence of pressure perturbations in the model chamber. In addition, the magnitude of the pressure perturbation was also correlated with the amount of water expelled from the model. A final report was written by ERC which outlined all the data analysis and the findings and is contained in Section 3.3.8.

### **1.3.9 RSRM Scaled Nozzle Slag Ejection Model**

This model was designed by ERC to support a higher fidelity investigation of the slag ejection phenomenon. The model included the RSRM aft segment, aft joint inhibitor simulator and a submerged nose nozzle scaled to the RSRM nozzle. The water injection would be done in the submerged nose region of the nozzle, approximately at the aft case/nozzle joint. These enhancements would allow the study of slag collection as well as expulsion from the model. Section 3.3.9 contains the pretest report for this task which outlined the model test conditions as well as instrumentation required for the test program. This model was also designed to examine the theory of the periodicity of the slag expulsion from the RSRM. A boroscope was used in the model to create a usable video record of the slag expulsion event. Section 3.1.1.1 contains an AIAA paper entitled "The Effects of Slag Ejection on Solid Rocket Motor Performance" which covers the work on this model in detail. This paper was presented at the 1995 AIAA Joint Propulsion Conference in San Diego and has subsequently been awarded the 1995 Solid Rockets Best Paper Award.

### **1.3.10 RSRM Inhibitor Dynamics Model**

As a result of concern arising in December 1994 over the stiffness of new NBR inhibitor material being installed in the RSRM boosters, a plan was developed to produce and test an RSRM Inhibitor Dynamics Model. A brief test program involving the NBR inhibitor material was performed using the 6.5% Slag Ejection Model. These tests provided timely information which was needed to address a critical flight readiness issue related to the stiffer NBR inhibitors. After these tests were successfully completed, it became apparent that follow-on testing would increase confidence in the Strouhal number correlations as well as provide the opportunity to further evaluate other NBR material samples as requested by the Materials Lab. The RSRM Inhibitor Dynamics Model was developed to make use of the 6.5% Slag Ejection Model hardware with some modifications and additions. The purpose of the model was to test the interaction between the inhibitor edge tone frequencies and the longitudinal frequencies of the motor. Additional data to be gained from the model was the effect of differing NBR material characteristics on the oscillating chamber pressure component. The model was constructed such that both the center and the aft joints could be modeled and tested at the same time. The details of this model can be found in Section 3.3.10.

### **1.3.11 RSRM 10% Scale Cold Flow Model**

At the cancellation of ASRM, project interest waned in the ASRM/Technology Model because of the plan to continue use of the current RSRM flight motor. ERC developed a plan, which was accepted by NASA/MSFC, to modify the ASRM/Technology Model into an accurately scaled RSRM model complete with mass addition. The model was designed to provide the RSRM Project Office with a test vehicle capable of high fidelity simulation and measurement of the internal flow environment and performance phenomena in the motor and nozzle as related to specific motor design and/or material upgrades or anomalous conditions. ERC has provided support for this project by setting forth the requirements of the model, defining the flow conditions of the model as well as the interior flow geometry and providing the necessary support analysis for the detailed operational aspects of the model. ERC reviewed the detailed design as presented by DEI to ensure the model as designed meets all model requirements. Details on this model can be found in section 3.3.11.

## **2.0 MAJOR CFD TASKS SUMMARIES**

### **2.1 Full Scale Motor Analyses**

ERC supported NASA/MSFC by performing CFD investigative analyses on several full scale solid rocket motors. Analyses were performed as verification analyses to evaluate motor designs and uncover potential operational problems or analyses to support problem resolution for existing operational motors. Thermal, mechanical and

chemical motor boundary conditions for the analyses were generated and provided to NASA as needed. Color graphics and plots were used to present the flow field analysis results in an easily understandable form. The full scale motors investigated include Titan IV, ASRM and RSRM. Summaries of the major analyses performed by ERC for each of these motors are contained in this section.

### **2.1.1 RSRM Motor Analyses**

ERC has supported the RSRM program by performing CFD analyses to evaluate developmental changes in the RSRM and resolve operational problems with RSRM in support of various investigative analysis teams. The major analysis activities are highlighted in this section.

#### **2.1.1.1 Pressure Perturbation Investigation**

Several CFD analyses were performed in support of the pressure perturbation investigation. This section contains a brief description of each of these analyses.

##### **2.1.1.1.1 Bent Inhibitor/Propellant Grain Pressure Loads**

The main purpose of the various analyses performed under this task was to determine the flow field induced structural loads on the propellant grain segments and the inhibitors at all three field joints for the 67 second burn time RSRM motor configuration with deformed inhibitors. Multiple inhibitor configurations were analyzed in order to gauge the effect of inhibitor length and deformation. These analyses collectively determined that the flow field induced pressure loads at the field joints were small and that flow field induced inhibitor failure was a low probability event. The inhibitor deformations computed compared well with previous Thiokol estimates. A particle tracking analysis was also performed to determine if aluminum oxide slag particles of various sizes could be trapped in the slots to form slag deposits on the inhibitors. The analysis showed that there was a propensity for larger particles to be trapped in the field joints and that there was a need for two-phase flow analysis of the RSRM motor. A detailed presentation of this work is contained in section 3.1.1.1.

##### **2.1.1.1.2 Aft Segment/ Nozzle Port Blockage Analysis**

The purpose of this analysis was to verify the motor port blockage required to cause a pressure blip of the magnitude observed in the flight motor RSRM-29B, STS-54. In order to accomplish this task, a blockage of the size previously computed by a ballistics model was placed in the motor port to simulate port blockage due to a large piece of failed inhibitor. This blockage was determined to be sufficient to create a pressure blip with the proper magnitude. However, the possibility of achieving this degree of blockage was judged to be highly unlikely. Section 3.1.1.1 contains a more complete description of this analysis.

### **2.1.1.1.3 Submerged Nozzle Cavity Investigation**

CFD was used to examine the flow field in the vicinity of the RSRM submerged nozzle and particularly in the area of the aft joint stiffener. The aft joint stiffener joint was of interest because of observed heavy erosion in this region of the motor. CFD analyses of the submerged cavity were performed for conditions in which the cavity was both empty and partially filled with slag. Section 3.1.1.1 contains detailed information on the analyses. The analyses determined that the nature of the recirculation in the submerged cavity region deters the flow of slag from the motor port surface into the submerged nozzle region at the aft stiffener joint. It was determined that the major difference in the flow fields for the two cases is that flow into the empty cavity is such that solid particles would tend to be entrained into the cavity. As the submerged cavity fills with slag, the recirculation flow is such that slag churned up at the slag surface would tend to be carried through the nozzle. This analysis highlights a possible mechanism for slag ingestion from the submerged nozzle region.

### **2.1.1.1.4 3-D Aft Segment/Nozzle Slag Pool Analysis**

A 3-D CFD analysis of the aft segment/nozzle region was performed to determine the nature of the flow field and in particular the circumferential pressure gradients and velocities in the cavity behind the submerged nozzle. The accumulated slag surface in the submerged cavity was slanted at an angle of  $6^\circ$  due to the fact that the motor flies at an angle of attack. The maximum circumferential pressure gradient existing in the submerged cavity was determined and significant circumferential velocities were found to exist under the conditions considered in the analysis. These circumferential velocities could enhance the ingestion of slag from the submerged cavity region. Section 3.1.1.1 contains more detailed information on the analysis.

### **2.1.1.1.5 Updated Bent Over Inhibitor Heights Analysis**

An analysis as described in section 2.1.1.1.1 was previously performed during early 1993 on the RSRM-29B, STS-54 motor inhibitors. Updated inhibitor heights obtained from Thiokol were used to perform a similar analysis to be sure that changes in the projected inhibitor heights did not change the conclusions of the original analysis. This analysis was completed and the conclusions concerning the pressure loads remained the same. The loads due to pressure differentials are small from a mechanical load standpoint and do not present a failure mode for the motor. Section 3.1.1.1 contains detailed information on this analysis.

### **2.1.1.1.6 Submerged Nozzle Cavity Slag Analysis**

In support of investigations into the amount of slag which was available for expulsion from the RSRM motor at the 67 second burn time, a two-phase CFD analysis was performed to determine the amount of slag which collects in the motor field joints and in

the submerged nozzle cavity. The analysis showed that the basic flow field features around the nozzle entrance are conducive to transport and collection of slag in the nozzle nose cavity after a burn time of approximately 50 seconds. The CFD results agreed with real time radiography measurements of static test motors which confirm slag slurry rotation in the submerged nose region. Using the results from this analysis along with previous predictions of slag accumulation, estimates were made of the total slag accumulated in the motor up to this burn time and a worst case pressure perturbation was estimated which was well within system safety concerns. Section 3.1.1.1 contains further information on the analysis.

#### **2.1.1.1.7 Full Scale Motor Slag Accumulation Analysis**

Two-phase flow analyses were planned for several motor web times in order to generate a curve of slag accumulation rate versus motor web time and ultimately the total quantity of slag accumulating in the motor submerged nozzle region as a function of web time. The amount of slag collecting in the field joints and in the motor head end region was also calculated. The analysis was to include the following set of burn times: 32.63, 49.57, 64.74, 79.75, and 110.83 seconds. This analysis is not complete but results for the 49.57, 79.75 and 110.83 second web times are detailed in Section 3.1.1.1.

#### **2.1.1.2 NBR Stiffness Investigation**

Several CFD analyses were performed in support of the NBR Stiffness investigation. These analyses relate to inhibitor deformations and the effects of NBR material on the accumulation of slag in the motor. This section contains a brief description of each of these analyses.

##### **2.1.1.2.1 Nominal and Stiff NBR Inhibitor Materials Analysis**

A CFD task to analyze the deformation and flow field disturbance effects associated with the nominal and stiff NBR inhibitor material used in RSRM was performed. This work included analyses of the forward, center and aft inhibitors. The goals of the CFD analysis were achieved as the following accomplishments. First, the coupled fluid dynamic/mechanical inhibitor deformation analysis showed that the stiffer NBR material deformed less than the nominal NBR material although the amount of slag collecting in the submerged cavity was almost the same for the two configurations. The final deformed inhibitor geometries were then used to perform a fully coupled two-phase flow slag accumulation analysis which showed only a minor change in slag accumulation for the stiffer NBR material. The final deformed geometry solutions were used to compute the paths of large droplets of slag released from the motor inhibitor tips to investigate the possibility of slag being released from field joints and accumulating in the submerged nozzle cavity. The flow field solutions for the nominal and stiff inhibitor materials were then analyzed to determine if a difference between the flow fields existed downstream of the aft inhibitor near the nozzle nose. The velocity



profiles were almost identical for the nominal and stiff NBR inhibitor motor configurations at a location just upstream of the nozzle nose. Flow field solution information near the inhibitor tips was also given to NASA/MSFC/ED33 so analyses to estimate vortex shedding and acoustic mode induced motor pressure fluctuations could be performed. Section 3.1.1.2 contains a complete description of this analysis.

#### **2.1.1.2.2 Inhibitor Height Effect on Slag Accumulation**

An analysis was performed for the RSRM 80 second burn time full scale motor geometry to determine the sensitivity of slag accumulation in the submerged nozzle region of the motor to inhibitor geometry variations. Section 3.1.1.2 contains a full description of this analysis. The slag accumulation analysis showed that as the inhibitor height increased, the amount of slag trapped in the submerged nozzle decreased due to disruption of the aft propellant surface velocity field. However, it was noted that the inhibitor heights must be significantly greater than projected by Thiokol before much effect on slag accumulation is noted. Also, more slag is collected in the field joints as the inhibitor length is increased. Changing the lengths of the inhibitors upstream of the aft inhibitor does not affect slag accumulation in the submerged cavity underneath the nozzle because particles collecting in the submerged region emanate from the aft propellant segment which is affected most by the aft inhibitor length and shape.

#### **2.1.2 TITAN Motor Failure Analysis**

A computational fluid dynamics (CFD) analysis was performed on the aft slot region of the Titan IV Solid Rocket Motor Upgrade (SRMU). This analysis was performed in conjunction with MSFC structural modeling of the propellant grain to determine if the flow field induced stresses would adversely alter the propellant geometry to the extent of causing motor failure. The results of the coupled CFD/stress analysis showed a continual increase of flow field resistance at the aft slot due to the aft segment propellant grain being progressively moved radially toward the centerline of the motor port. For more information on this analysis, a detailed report on the Titan IV SRMU CFD investigation is contained in Section 3.1.2.

#### **2.1.3 ASRM Motor Design Verification Analyses**

ERC performed many CFD analyses to evaluate and verify the design of ASRM. Motor components examined included the propellant grains, field joints, inhibitors and submerged nozzle. Major analysis activities in support of the ASRM project are highlighted in this section.

### **2.1.3.1 Motor Port Environment Analyses**

As part of the overall ASRM design evaluation effort, CFD was used to evaluate the flow induced thermal and mechanical environments in the region of the major internal motor components. These CFD analyses included investigation of all the field joints, the propellant and the motor nozzle. The internal motor environment analyses revealed no design problems associated with any of the components investigated. The individual analyses are discussed in this section.

#### **2.1.3.1.1 Slot/Port Flow Interaction Analysis**

The flow field in the region of the ASRM field joints was examined as a first step in assessing the design of the ASRM forward and aft field joints in order to assure the proper operation of the motor prior to further development or test firing. This analysis determined that the pressure loads at 0 second burn time are too small to cause a slot deformation problem which would result in motor failure. It was also determined that the pressure loads on the propellant grain at the motor joints at the 19 second burn time are significantly affected by the inhibitor height and orientation. The CFD results showed that this analysis should be extended to include actual deformed grain and eroded inhibitor geometries. It was also concluded that a coupled structural/fluid dynamic stress analysis should be performed to assess the deformation loads resulting from slot/port flow interactions. This analysis is explained in more detail in Section 3.1.3.1.

#### **2.1.3.1.2 Full Scale Aft Section/Nozzle Analysis**

A CFD analysis of the full scale Aft Segment/Nozzle was performed in order to provide a high fidelity flow field solution in the region of the ASRM submerged nozzle. The flow field predictions for velocities, temperatures and pressures were made available for use in other evaluation analyses of the aft section motor components. Section 3.1.3.1 gives a complete description of the results of the analysis.

#### **2.1.3.1.3 Full Motor Port Analysis**

A CFD analysis was performed on the full scale motor from the motor head end to the nozzle throat. Results were made available for use in subsequent design evaluation analyses. Results from this analysis were compared to CFD simulation results of the ASRM Technology model flow field. This comparative process allowed the understanding of some previously unexplained motor phenomena such as the underprediction of the pressure drop down the motor port by ballistic codes at early motor burn times. It was determined that this phenomenon is related to the flare of the propellant geometry existing in the aft segment of the ASRM (as well as RSRM) design. Section 3.1.3.1 contains detailed information on this analysis.

### **2.1.3.2 Coupled Structural/Fluid Dynamic Stress Analysis**

A coupled fluid dynamic/structural stress analysis was performed to examine the deformations at the motor field joints because of a recommendation made in the original ASRM slot/port flow interaction analysis reported in section 2.1.3.1.1. This analysis included the effects of cure and thermal shrinkage for the most stressing initial propellant temperature, 1g vertical storage, 0.6g flight acceleration, and 2-D pressure loads. The analysis concluded that a significant portion of the propellant deformation at the aft slot was due to 2-D flow effects but that the slot deforms to a stable configuration when fluid dynamic pressure loads are considered. The overall conclusion was that the deformations on the propellant field joint were not excessive and the possibility of motor failure as a result of fluid dynamic loading was not a problem. Section 3.1.3.2 contains a detailed presentation of the method used to perform the coupled structural/fluid dynamic analysis and a summary of the results.

## **2.2 Subscale Motor Analyses**

CFD analyses were performed for two subscale motor tests to support NASA/MSFC. Analyses were performed in support of data analysis for the NITM two-inch motor tests and complete design and data analysis CFD investigations were performed for the spin test motor.

### **2.2.1 NITM-2 Test 3 Data Recalibration Analysis**

CFD predictions and 1-D ballistics were utilized along with pressure measurements from past Two-Inch Motor tests and information on the Test 3 instrumentation setup to determine that there was an electrically related calibration problem for the gauges in the first three rings of the blast tube. ERC also formulated a method for recalibrating the pressures in the first three blast tube rings using CFD predictions along with previous test data. The Test 3 pressures were brought into agreement with the last two material ring pressures. Section 3.2.1 contains a detailed explanation of the process used to a posteriori recalibrate the Test 3 pressure measurements. This recalibration of the pressure data allowed the Test 3 results to be used to accurately evaluate the erosion resistance of the various insulation materials used in the test.

### **2.2.2 Five-Inch Spin Motor Design and Test Analysis**

ERC provided CFD support to NASA/MSFC during both the design and test phase of this program. CFD analyses of various spin motor nozzle configurations were performed to design a positive trap for the slag that would increase the measured slag weights. Two-phase fluid dynamic analyses were performed to develop a nozzle nose design that maintained similitude in major flow field features with the full scale RSRM and to select an appropriate spin rate along with other considerations, such as avoiding burn rate increases due to radial acceleration effects. Detailed predictions for slag accumulation weights during motor burn compared favorably with slag weight data

taken from defined zones in the subscale motor and nozzle. The use of two-phase flow analysis proved successful in gauging the viability of the experimental program during the planning phase and in guiding the design of the critical submerged nose nozzle. Section 3.2.2 contains a complete description of the design and experimental test analysis of the spin test motor.

## **2.3 Cold Flow Analyses**

ERC supported NASA/MSFC by performing CFD analyses on SAF facility components and models. These analyses were used to assure the proper operation of the facility, to verify model design and operation and to provide detailed understanding of the flow field in the various models. The CFD task performed will be summarized in this section.

### **2.3.1 Checkout Model**

ERC's CFD support to NASA/MSFC for the checkout model included the detailed modeling of all major facility flow components in order to test the proper operation of the facility prior to model testing. ERC performed 3-D CFD analyses of the model from the header pipes through the diffuser which were able to predict the proper operation of the facility prior to testing. The details of this analysis can be found in Section 3.3.1 along with a JANNAF paper on this topic.

#### **2.3.1.1 SAF Checkout Model 3-D Flow Field Analyses**

In order to verify the design and operation of the SAF facility, a 3-D CFD analysis was performed on the major facility checkout model components. The analyses included examination of the flow field in the header pipes, metering nozzles, adapter chamber, spool pieces, model nozzle and diffuser. Objectives of the analyses included the determination of the extent of asymmetric flow effects created by the manifold system and adapter chamber, performance of the metering nozzles, model nozzle and adapter chamber, uniformity of the flow in the checkout model chamber and spool pieces and the operation of the diffuser. The analysis verified that choked flow occurs in both the metering nozzles and the model nozzle, the manifold system performs as expected, the adapter and transition sections perform well in delivering a uniform flow profile to the model nozzle, and the predicted shock structure in the diffuser indicates the design will perform as expected.

#### **2.3.1.2 2-D Effects in the Checkout Model Nozzle**

During the process of analyzing the Series I test data, it was determined that the measured pressure ratio at the model throat was significantly lower than the 1-D theoretical ratio. CFD was used to show that there was a physical basis for the lower measured pressure ratio. The CFD solution showed that significant 2-D effects were present in the model nozzle throat region where the measurement was taken. The

analysis also provided an alternative measurement location for accurately determining the model mass flow rate. Section 3.3.1 provides further detail on the comparisons between the test rig measurements and the CFD flow field predictions.

### **2.3.2 ASRM Technology Model Analysis**

In order to provide a detailed assessment of the design of the Technology model and the internal flow field similarity between the model and the ASRM full-scale motor, CFD analyses were performed on both the Technology model and the full-scale motor. The CFD analysis of Technology Model flow field confirmed the proper operation of the model and also provided insight into a major feature of the motor flow field. The proper prediction of transition of the flow down the motor port was illustrated. This phenomena was verified by the proper prediction of the pressure drop down the motor port. Section 3.3.2 contains detailed information on the Technology Model analysis.

### **2.3.3 ASRM Aft Section/Nozzle Model**

A CFD analysis on the ASRM 8% scale Aft Section/Nozzle Model was performed. Predictions of the 8% scale model were made in order to make comparisons between measured and predicted flow field quantities for the model. The numerical computation of the model aft segment/nozzle flow field was necessary in order to further validate the CFD code for this type of motor problem so that better predictions for full scale configurations can be made. A validated CFD prediction was also necessary in order to provide a more complete representation of the flow field in the aft section/nozzle region because only a small set of flow field quantities can be measured in any actual experiment. The computational flow field compared well with the experimental results and illustrated several salient features of the flow field not noted in the experimental data. Section 3.3.3 provides a complete description of the results of the model analysis if further information is desired.

### **2.3.4 ASRM Aft Section/Nozzle Water Flow Model Analysis**

Initial experimental data collected from the water flow facility downstream of the velocity profile plate showed that an irregular Culick velocity profile was produced by the drilled-hole plate instead of the desired Culick profile. A CFD investigation of the water flow model was initiated to determine if these results could be duplicated for a computational solution. The complete presentation of this analysis is contained in section 3.3.4. The CFD analysis confirmed that there was a significant downstream dependency of the flow on the inlet velocity profile and changes were made to the original velocity profile plate to achieve a smoother profile.

## **2.4 CFD Analysis Capability Development**

### **2.4.1 $\kappa$ - $\epsilon$ Equation Coefficients Adjustment**

A CFD analysis of the internal flow field of a simulated cylindrical port solid propellant rocket motor was performed by ERC in order to determine the proper  $\kappa$ - $\epsilon$  model coefficients for internal flow configurations. This effort became necessary because the standard coefficients used in the model produced too rapid a transition of the flow down the port and therefore too much pressure drop in the motor. The adjusted coefficients, obtained by experimental data comparisons produced flow field results that compared to ballistic results. Section 3.4.1 contains detailed information on how the analysis was performed as well as presenting comparisons of the experimental and CFD results.

### **2.4.2 Procurement of the CELMINT CFD Analysis Code**

In order to increase ERC's capability to make two-phase flow predictions for NASA/MSFC projects, the CELMINT (Coupled Eulerian/Lagrangian Multidimensional Implicit Nonlinear Time-dependent) code was obtained. The code was developed by and obtained from SRA, Inc. (Scientific Research Associates) of Glastonbury, Connecticut, during the month of December 1993. Over the period of performance of the contract ERC, with the help of SRA, made many modifications to the code to provide more capability for two-phase flow boundary conditions and corrected some of the errors in earlier versions of the code through an extensive ongoing validation effort.



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<b>VIII. EXPIRATION OF REVIEW TIME</b> The document is being released in accordance with the availability category and limitation checked in Section II since no objection was received from the Program Office within 20 days of submission, as specified by NHB 2200.2, and approval by the International Affairs Division is not required. Name and Title: _____ Office Code: _____ Date: _____ Note: This release procedure cannot be used with documents designated as Export Controlled Documents, conference presentations or foreign publications.										
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